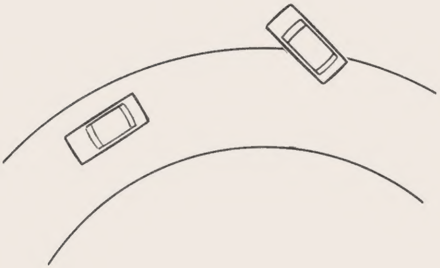
THINGS of science



MOTION

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MOTION

A car rounding a corner, a rocket speeding upward into the skies and a child walkng down the street all have something in common—they are obeying Newton's laws of motion.

In 1686 Sir Isaac Newton published his three laws of motion. All objects move according to these laws which form the basis of classical mechanics. Today, almost 300 years later, we still apply these laws to send spacecraft to the moon or place satellites in orbit around the earth.

The study of motion itself is known as kinematics, while the cause of motion or change in motion is referred to as dynamics.

In this unit we shall observe the behavior of objects in motion and relate their movements to Newton's three laws of motion.

First look over your materials.

MARBLE

LEAD SINKER

PAPER CUP

BALLOON

TOOTHPICKS—Two.

CARD—3 x 5-inch colored card; for constructing wagon.

DIE-CUT CARD—3 x 5 inches; for constructing wagon.

STRING

FIRST LAW OF MOTION

Experiment 1. Place your THINGS of science box on a table. You know that unless you move it the box will remain in the same position indefinitely.

Now push it, then pull it. These actions of pushing and pulling to make an object move are called forces. The forces are external since they are applied by an outside agent, your hand.

Newton stated in his first law of motion that a body at rest tends to remain in a state of rest and a body in motion to remain in uniform motion along a straight line unless an unbalanced external force acts upon it to change that state.

You have just demonstrated the first part of the first law of motion.

External forces may be from a variety of sources, such as muscular force, gravitational force, magnetic force or the forces due to heat and electricity. When you moved the box, you applied muscular force. If the box is dropped to the floor gravitational force causes the motion. An iron nail can be made to move by magnetic force.

When an object is at rest, the upward forces acting upon it are equal to the downward forces and the sum of the horizontal forces from opposite sides are equal to each other. Therefore, the object remains stationary or in equilibrium. If any of the forces acting upon it become

unbalanced, that is, if one becomes greater than another, then motion occurs. An external force must be exerted, however, for this to happen. An object cannot move of its own accord.

Experiment 2. Place a marble on a smooth polished surface and tap it to start it rolling. Note that it travels along a straight line and at a constant rate initially.

The second part of Newton's first law states that a body in motion tends to remain in uniform motion unless acted on by an unbalanced force. A body in motion has a certain velocity and tends to retain that velocity, in other words, maintain a constant velocity or uniform motion.

The terms velocity and speed are often used interchangeably in everyday language. However, technically, speed refers only to the rate at which an object is traveling, say 30 miles per hour. The rate is called the magnitude of the motion. Velocity on the other hand includes direction as well as magnitude. Thus, the velocity of a car would be, for example, 30 miles per hour in a northward direction. Velocity is always related to direction of travel, while speed never includes direction. Therefore, in speaking of motion, constant velocity also implies direction. Quantities that include both magnitude and direction are called vec-

tors. Those that concern magnitude only, such as speed, are known as scalars.

Now roll your marble again. While the marble is traveling at a constant velocity, there is no unbalanced force acting on it strong enough to reduce its velocity. However, friction is always present and acts as an opposing force gradually slowing the marble down until it finally comes to rest. What causes friction?

FRICTION

Experiment 3. Note the fairly smooth surface of the THINGS box. Place it on a very smooth surface and give it a push. Observe how far it moves. Now place it on a rug and push it with a similar force. Compare the distances traveled. As you probably expected, the box covered a greater distance on the smooth surface than on the rough carpet.

When one object moves along the surface of another, friction occurs because irregularities on the surface of the two bodies tend to get caught in each other. The more irregular both surfaces are, the greater the frictional force created. The frictional force acts as an external unbalanced force that opposes a moving body, retarding it and finally causing it to stop.

You are aware that a smooth object on a very smooth surface will glide along

with the greatest of ease, like the puck in an ice hockey game. But even the puck, if allowed to travel as far as it can go, will eventually come to rest. Since no surface is absolutely smooth, friction cannot ever be completely eliminated.

Roll the marble across the floor and note how much further than the box it travels before coming to a stop. A round object encounters less frictional force than a flat one. Thus, the reason for wheels.

As we move about, we are continuously opposing the friction of the air around us. When we walk, we must push molecules of air aside to move forward. In swimming, the water molecules exert a frictional force on our bodies. Such forces due to the air and water are known as viscous forces and create a frictional drag. If you walked through a perfect vacuum completely devoid of air molecules, then you would meet no viscous force. An airplane making its way through the atmosphere must fly against frictional drag, but a spacecraft orbiting the earth in deep space encounters almost no friction on its travels.

The marble rolling across the table is slowed by viscous force as well as surface friction no matter how small the force.

In order for a moving body to maintain constant velocity, a force equal to all retarding frictional forces must be

exerted.

An automobile at rest is in static equilibrium. If it is in motion at a constant velocity, it is in dynamic equilibrium even though force must be applied by using more gas to maintain the velocity against frictional forces. An object moving at a constant velocity is in equilibrium because it has no unbalanced forces acting on it.

But why does a body at rest tend to remain at rest and one in motion to continue in motion? This is because of a property common to all matter—inertia.

INERTIA

Inertia is that property of matter that resists any change in motion.

Experiment 4. Place your THINGS box on a smooth surface. It remains there because of inertia. Now give it a push. It moves because of the unbalanced force applied that is great enough to overcome its inertia.

Experiment 5. Now place your box on a sheet of notebook-size paper. Then with a quick movement jerk the paper out from under the box. Does the box remain behind? The force of friction between the paper and box is not great enough to overcome the inertia of the box so it stays behind.

Experiment 6. Take the yellow card in your unit and place it across the top of

a glass. Put a marble in the center of the card and then jerk the card away. What happens to the marble? Here again, the inertial force is greater than the frictional force so the marble remains where it was and falls into the glass.

In order to move an object, no matter how large or small, inertia must first be overcome.

Experiment 7. Obtain two milk cartons; one filled with liquid and the other empty. By their outer appearance you should not be able to tell which is filled and which empty. Place the two side by side on a table and ask a friend to push the filled carton along the table. Next, without letting him know it is empty, tell him to push the second carton. If he pushes the second carton with the same force, believing it will show the same resistance as the first, he will be surprised at how much more easily it moved and how much further it traveled. From this observation you can conclude that the inertia of the filled carton is greater than that of the empty carton. A heavy object has more inertia than a light one.

In order to provide the force needed to overcome inertia, energy must be supplied. This energy may be body energy as in moving the cartons, chemical energy from burning fuel in jet planes, mechanical energy or energy from any other source. But unless some sort of energy is

provided to supply the force, a body at rest will remain at rest.

The inertial resistance of bodies to change in motion causes certain responses of objects that we encounter almost every day.

We can demonstrate some of these effects on a small scale.

Construct a wagon from the plain yellow card and die-cut orange card.

First make the body of the wagon. Draw lines ½ inch from each edge of the yellow card. Fold along the solid lines and cut along the dotted lines as shown in Figure. 1.

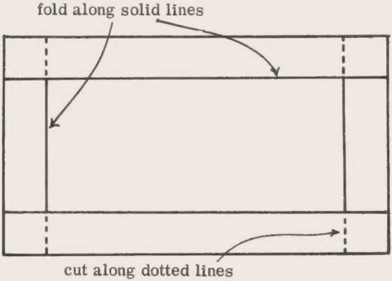

Fig. 1

Make square corners and tape or paste the seams together to form a box-like structure. This is the wagon body.

Separate the wheels, washers, rectangles and handle from the die-cut card (Fig. 2).

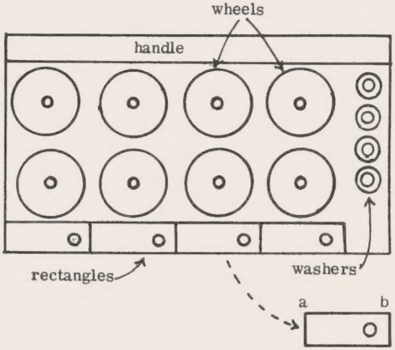

Fig. 2

Paste two wheels together so that you will have four wheels of double thickness. Punch out the center holes.

Take the four rectangular pieces and note that the hole in each is slightly further from one side (**a** in Fig. 2) than

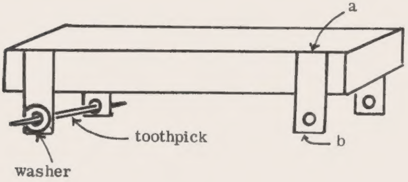

Fig. 3

from the other (**b** in Fig. 2). Paste the strips onto each side of the wagon body about ¼ inch from the end with edge **a** flush with the top of the wagon (Fig. 3).

Pass the toothpicks through the holes. They will serve as axles for the wheels. If you wish, rub the toothpicks with wax to reduce friction.

Insert the washers on the axles on each side. Adjust the axle so that an equal amount of it extends beyond each side.

Next, put a small amount of strong glue, such as epoxy glue, in the hole of the wheels and insert them onto the toothpick, pushing the wheel to about 1/16 inch from the side. Check to see that the remaining length of the toothpick protruding from the wheel is about the same on each side. Push the wagon back and forth to see that it rolls easily. When the wheels are properly adjusted, allow the glue to dry completely so that the wheel is tightly secured to the axle. Apply more glue if necessary. To assure that the wheels will not fall off the axle, wind a little tape tightly around the part of the toothpick extending beyond the wheel.

Next take the strip for the handle. Bend it slightly about ¾ inch from one end. Glue ½ inch of that end to the center of the bottom of one end of the wagon. Your wagon is now complete (Fig. 4).

Cut a 1/16-inch strip about 2 inches

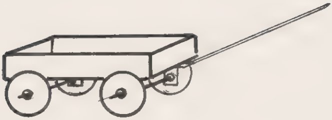

Fig. 4

long from the remaining orange paper and fold it into an equilateral triangle about 3/8 inch to a side. Glue the free ends together (Fig. 5).

Fig. 5

This triangle will serve as a holder for the marble if needed.

Experiment 8. Place a marble in the center of the wagon. If it will not remain in position because the wagon is not exactly level, use the triangle above as a platform to hold it in place.

Pull the wagon very gently and the marble will remain in place, moving along with the wagon. Slowly stop the wagon and then start it suddenly forward with a quick movement. What happens to the marble? Does it behave according to the first part of the first law of motion? An object at rest tends to remain at rest due to inertia. Therefore, although the wagon

moved forward, the marble remained behind and appeared to move backward. In the same way, passengers standing in a bus are "thrown" backward if the bus starts suddenly and unexpectedly.

Experiment 9. Put the marble near the center of the wagon again. Pull the wagon along at a constant velocity and at a rate that keeps the marble in position. Then stop it suddenly. What happens to the marble this time? Does it move forward or backward?

The second part of the first law states that an object in motion tends to remain in uniform motion. Inertia resists any change in motion and causes a moving body to continue in a straight line at a constant velocity. Therefore, the marble continued to move forward when the wagon stopped.

Experiment 10. Use a paper clip or other small object like a button as the "passenger" this time. Place a book about six inches in front of the wagon. Give the wagon a sudden hard push from the back so that it rolls with some force into the book. What happens to the object? This shows how an occupant in a stopped car is thrown when the car is struck with force from the back and then meets an obstacle directly in front of it. The person is thrown backward and then forward by the impact.

Experiment 11. Roll the marble across

a smooth surface. Notice that it travels in a straight line. Now place an object along its path. What happens when it strikes it? The object serves as an external force that changes the direction of motion along a different straight line. According to Newton's first law, a moving object tends to travel with a constant velocity along a straight line unless acted on by an external unbalanced force.

A body once in motion tends to continue in motion unless an external force is applied. Thus, an automobile needs a great force to start it moving, but once in motion only a small force is needed to keep it going at a constant velocity. However, in order to stop it force must be exerted to counteract the inertia; usually the frictional force of the tires against the roadway when the brakes are applied. A body cannot change its velocity, increase or decrease it, by itself. An independent external action is necessary to produce the change.

Experiment 12. Place a paper clip or button in the wagon and pull it along at a constant velocity, then turn a corner sharply to the left. Which way does the object move?

Since velocity is a vector, having direction and magnitude, and inertia resists any change in motion, the paper clip moved to the right side of the wagon along a straight line when your wagon

turned left.

The same thing happens when one turns a corner in a car rapidly. Any packages lying loose on a seat will slide in the original direction the car had been traveling. We should note here that a car rounding a corner does not have uniform velocity even though it maintains the same speed, since it is changing direction continuously.

In the absence of all impeding forces, a body placed in motion would keep moving forever.

SECOND LAW OF MOTION

Newton in his second law of motion stated that if an unbalanced force acts upon a body, the body will be accelerated and the magnitude of the acceleration is proportional to the magnitude of the unbalanced force and the acceleration is in the direction of the force. His law is also expressed in the form of the equation,

$$\text{force} = \text{mass times acceleration}$$

$$\text{or,} \quad f = ma$$

Acceleration is the change in velocity per unit time. Like velocity, it is a vector, having both direction and magnitude. It is expressed as

$$a = \frac{v}{t}$$

where a is acceleration, v is velocity and t is time.

The mass of an object is a property of the substance. A steel ball of the same size as your marble would have a greater mass than the marble, while a ball of cotton of the same diameter would have a smaller mass. These differences are due to the nature of each of the substances.

In everyday life, we recognize a lesser or greater mass by its weight. The weight of a substance results from the acceleration of the mass due to gravity. Since the acceleration due to gravity varies with location, (the distance from the center of the earth), weight may vary from place to place, but mass being a property of the substance itself will remain the same whether at sea level or on the moon. Thus, weight is expressed as mass times gravitational acceleration, or

$$w = mg$$

where w is weight, m is mass and g is gravitational acceleration.

A substance with greater mass will have greater weight as you can see from the above equation.

Experiment 13. Give a gentle tap (unbalanced force) to your marble placed on a smooth surface. Note that it is accelerated along a straight line at a moderate velocity.

Now give it a tap of greater force. Observe how much faster it travels. The greater the unbalanced force, the greater the acceleration. Experiments have shown that if the unbalanced force on a body is increased, its acceleration is increased proportionally. For example, if the unbalanced force is doubled, the acceleration of an object is doubled.

Acceleration is the rate of change in velocity. Therefore, in order to steadily accelerate an object, a steady unbalanced external force must be applied. The velocity of a moving object may be decreased or decelerated as well as accelerated. Decrease in velocity is also referred to as negative acceleration. Just as with acceleration, an external force is necessary to decelerate an object. Thus, to slow down a car, you would apply the brakes.

Experiment 14. Pull your wagon at a constant velocity, then accelerate it by pulling harder. Note that in order to accelerate the wagon you must apply more force. If once you accelerate the wagon and then maintain a constant velocity, the wagon is in dynamic equilibrium. In order to accelerate it further,

additional force must be exerted. If you reduce the force, the wagon is immediately decelerated.

To accelerate an automobile, the driver must press harder on the accelerator to supply increased force. The amount of acceleration is proportional to the force supplied.

In order to change the velocity of any object, an unbalanced force must be applied. A body cannot accelerate or decelerate itself.

Experiment 15. Place the two cartons, one filled and the other empty, on the table side by side. Now push them both at the same time with equal force. Note how much greater the empty carton is accelerated than the filled one.

When the unbalanced force is the same, the acceleration is inversely proportional to the mass. This means that the heavier the object, the more force required to move the object, as you can see from the equation,

$$f = ma$$

$$\text{and,} \quad a = \frac{f}{m}$$

If the weight of an object is doubled, the acceleration is halved, when the force

is constant. If we represent the constant force f as k, then

$$\text{acceleration} = k(1/\text{m})$$

Then if the mass is doubled, $a = k(1/2m)$; if the mass is increased four times, acceleration is reduced to ¼ and so on.

Experiment 16. Now increase the force on the filled carton, to match the acceleration of the empty carton. To give the two the same acceleration the force applied to the heavier carton must be increased proportionally to the mass. If the filled carton is 10 times as heavy as the empty one, then the force applied must be 10 times as great, since $f = ma$.

Experiment 17. Roll the marble along slowly so that it strikes your hand, noting the force of the impact. Now roll it with much increased acceleration against your hand, and observe the much larger force exerted on your hand. The greater the acceleration, the greater the force.

Experiment 18. Have someone push (accelerate) your empty THINGS box against your hand with a fairly rapid velocity. Notice the force with which the box strikes your hand. Now ask him to push a heavy book against your hand with the same acceleration. Is the force exerted on your hand greater? The greater the mass the greater the force when the

acceleration is the same.

When a body is in motion it acquires momentum which is expressed as the product of mass times velocity, or

$$p = mv$$

where p is momentum, m is mass and v is velocity.

Thus, the greater the mass and velocity of a moving object, the greater its momentum. The momentum of an object may be regarded as a measure of the difficulty encountered while stopping it when it is in motion. It is a vector quantity having direction and magnitude.

Experiment 19. Which object would have greater momentum? A marble traveling at great velocity or a book being pushed slowly across the table?

Since momentum is the product of mass times velocity, a small object, such as the marble, traveling at high velocity would have more momentum than the book moving slowly. A car traveling at 70 miles per hour has a greater momentum than one of the same mass traveling at 20 miles per hour and takes longer to stop.

Experiment 20. Push your THINGS box across the table. Note that it is accelerated in the direction of the force applied. Push it from the left side. It moves to the right. Apply the force from

the right and the box is accelerated to the left. The second law states that force and acceleration are in the same direction.

Experiment 21. Can you demonstrate by using your wagon how a passenger in a car is governed by the second law of motion, $f = ma$, in the event of a collision?

FREELY FALLING BODIES

Newton formulated the Law of Universal Gravitation which states that every body in the universe attracts every other body with a force that is proportional to the product of the masses of the bodies and inversely proportional to the square of the distance between their centers. Because of its mass, the earth exerts an unbalanced force of attraction on all objects on the earth's surface. This unbalanced force gives an acceleration to freely falling bodies of 32 feet per second per second.

Experiment 22. Place your marble on the table. It remains there because the force of the upward push of the table is great enough to counteract the downward pull of the gravitational force on the marble. If the table is removed the marble will fall to the ground because the unbalanced force due to gravity gives it motion.

Drop a heavy book to the floor. Which falls with greater force, the marble or the book? The answer is obvious and is according to the second law, $f = ma$, or $f = mg$, where g is the acceleration due to gravity.

THIRD LAW OF MOTION

Whenever one body exerts a force on another, the second force always exerts on the first a force that is equal in magnitude and opposite in direction. Or, for every action there is an equal and opposite reaction. This is Newton's third law of motion.

When we walk we push against the ground and the ground pushes back with an equal force.

When you pull your little wagon it pulls back with an equal force. Forces always occur in pairs. A single force never exists. It is always accompanied by an opposing force. However, although action and reaction are equal and opposite they do not balance each other because they do not act on the same object.

Experiment 23. Push your THINGS box. Your finger exerts a force on it and the box reacts with an equal and opposite force on your finger. The opposite forces are equal but are exerted on different objects and are not in equilibrium.

Experiment 24. Action and reaction are always equal. Slap a table gently. It hits you back with an equal force. Now slap it down hard. Since you slapped it hard, it struck you back with a force equally hard making your hand sting. The greater the action, the greater the reaction.

Experiment 25. Blow up your balloon and then twist the mouth holding it tightly to keep the air from escaping. Place the paper cup over the closed end of the balloon and lightly tape it to it (Fig. 6).

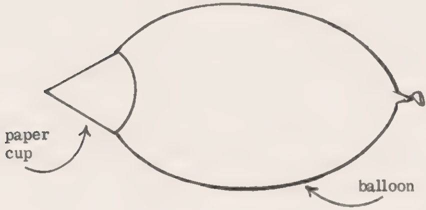

Fig. 6

With the tip of the cup pointing upward, release the balloon. Note how it shoots up into the air.

The molecules of compressed air in the balloon are forced out of the balloon at high velocity by the pressure of the

elastic walls. The reaction force of the air molecules pounding against the closed end of the balloon causes it to move in a direction opposite the open end. When the compressed air has all escaped, the balloon stops moving upward.

The basic principle of the movement of the balloon and a rocket shooting up into the sky is the same, Newton's third law of motion, action and reaction. The jet engine in a rocket consists of a long tube closed at one end and open at the other. Fuel is burned in the engine producing a high pressure of expanding gases. Since the front end of the tube is closed, the walls of the engine exert a great force on the gases which rush out of the rear opening with great velocity. As they do so, the gases exert an immense reaction force on the closed end forcing the rocket forward at high speed. This force is known as the thrust. The rocket and the jet stream of gases are both accelerated but in different directions.

Thus, the jet engine is a device that makes use of the third law of motion. It pushes away a tremendous volume of hot gases in one direction and makes use of the reaction force to thrust the rocket in the opposite direction with an equal force.

To place men on the moon, as you know, three-stage rockets were used, each stage providing the necessary thrust to achieve the required velocity and desired

distance.

When an astronaut wishes to change the direction of a spacecraft, he releases a spurt of gas. To move to the left, a jet of gas is released from the right. Why?

Experiment 26. Place your THINGS box and a heavy book about a foot apart, slide them toward each other so that they collide with force. Which was the hardest hit, the box or the book, or neither?

Which was thrown furthest by the impact? Why?

CENTRIPETAL AND CENTRIFUGAL FORCES

Experiment 27. Tie one end of your string to the wire loop on your sinker. Be sure it is securely fastened. Swing the sinker around in a circle. As you do so, you will see that the direction of the sinker is continually changing since it cannot travel along a straight path.

As you swing the sinker around, note the pull on the string. The sinker in motion tries to move along a straight line, but the string pulls it toward the center of the circle. Thus, the force on the sinker is exerted toward the center. This force that acts toward the center is known as the centripetal force.

Newton's second law applies to various kinds of motion including uniform circular motion like that of your sinker whirled on a string. But when an object

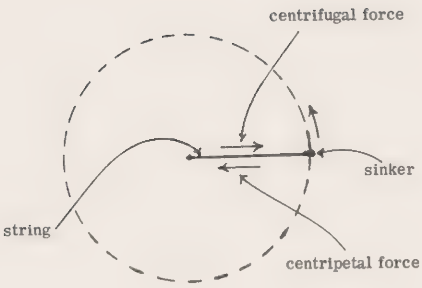

Fig. 7

moves in a circular path, it is constantly changing direction while the magnitude of its velocity remains the same. The centripetal acceleration it undergoes is its velocity squared divided by the radius of the circle, or

$$a = v^2/r$$

Since $f = ma$, then

$$f = m(v^2/r)$$

the centripetal force.

By Newton's third law, if the string exerts a force toward the center on the sinker, the sinker must exert an equal and

opposite force away from the center on the string. The force away from the center and acting on the string is known as the centrifugal force. The centrifugal force is the reaction to centripetal force and is equal and opposite to it (Fig. 7).

Experiment 28. Using about 12 inches of the string as the radius, whirl the sinker. Now increase its velocity. Is the pull on the string greater or less? The force increases with velocity.

As you continue to swing it at the same velocity, lengthen and shorten the string. Does the force of the pull increase or decrease when the radius is increased? When the radius is decreased? Refer to the equation, $f = m(v^2/r)$. Mass is constant here.

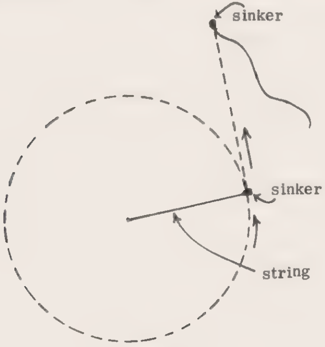

Fig. 8

Experiment 29. Now swing the sinker in a circle on the surface of a smooth floor. Then let the string go. In which direction does the sinker move? Does it continue in a circular direction or go off in a straight line?

The sinker obeys the first law of motion and continues in the same direction it was traveling at the moment, in a straight line and at a tangent to the circle (Fig. 8).

When you let go of the string and the sinker moved off at a tangent, what force acted upon it? Was it centripetal force or centrifugal force or neither? The sinker responded to inertial force according to the first law.

The centripetal force which kept it going in a circle and changing its direction disappeared when the string was released. Likewise the centrifugal force having nothing to react to also vanished.

Experiment 30. Make a handle for your paper cup with about 12 inches of the string and then tie the rest of the string to it (Fig. 9).

Place your marble in the cup and then swing the cup around in a circle perpendicular to the earth. First swing it slowly. Does the marble fall out? Increase the velocity. Does the marble remain in the cup this time? Can you explain why?

Go outdoors and repeat the experiment filling the cup half full of water. Can

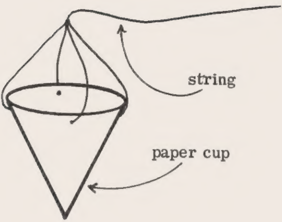

Fig. 9

you keep the water in the cup?

Both the marble and water remain in the cup when the velocity is great enough. To cause an object to travel in a circle, a force must be exerted on it that acts toward the center of the circle. In these experiments the paper cup supplied an inward centripetal force. However, if the velocity is too low or the radius too great, the centripetal force may not be sufficient to keep the body moving in a circle.

When a car turns a corner on a perfectly level road, the frictional force of the tires against the roadway supplies the necessary centripetal force. If the road is coated with ice, however, there is less friction and therefore insufficient centripetal force and the car skids off the road obeying the first law. Roads are often banked to prevent cars from sliding off at a tangent. If the road is banked at

a suitable angle, the roadway acts to keep the car moving in a circle, pushing it only in the direction perpendicular to its surface to supply the necessary centripetal force. The car may then round the curve without the aid of frictional force. Of course the car must be traveling within the maximum speed for which the road was banked.

As the car rounds a curve, the centripetal force exerted by the seat belt against your body keeps you going in a circle, just as the paper cup acted on the marble. Centrifugal and inertial forces cause your body to exert pressure against the seat belt. A seat belt must be strong enough to withstand these forces.

The spin dryer in a washing machine applies Newton's first law. The wet clothing is rotated rapidly and the water flies off in a straight line at a tangent through the holes in the cylinder wall.

The centripetal force that keeps a satellite circling the earth is the gravitational attraction. An equal and opposite force, the centrifugal force, acts on the gravitational force just as on the string attached to the sinker, keeping the satellite from falling to the earth.

Centrifuges to separate liquids of different densities is another application of centripetal force.

There are many ways in which Newton's three laws of motion are applied in

our daily lives. See how many you can observe by just looking around you.

If you are interested in delving further into the subject various physics textbooks will be helpful.

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